LUNAR BASE CELSS— A BIOREGENERATIVE APPROACH

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G. W. Easterwood[1], J. J. Street[2], J. B. Sartain[3], D. H. Hubbell[2], and H. A. Robitaille[1]

During the twenty-first century, human habitation of a self-sustaining lunar base could become a reality. To achieve this goal, the occupants will have to have food, water, and an adequate atmosphere within a carefully designed environment. Advanced technology will be employed to support terrestrial life-sustaining processes on the Moon. One approach to a life support system based on food production, waste management and utilization, and product synthesis is outlined. Inputs include an atmosphere, water, plants, biodegradable substrates, and manufactured materials such as fiberglass containment vessels from lunar resources. Outputs include purification of air and water, food, and hydrogen (H_2) generated from methane (CH_4). Important criteria are to (1) minimize resupply from Earth and (2) recycle as efficiently as possible.

INTRODUCTION

On the Earth, we exist within a dynamic life support system. Our atmosphere is maintained at static concentrations of certain gases by exchange with living organisms and physiochemical processes. Our water is continually being purified by evapotranspiration and by nature's filtering system, the soil. Nutrients, essential ions and compounds necessary for life, are immobilized by living organisms. Geochemical mineralization and decomposition of natural or synthetic biodegradable organic substrates are sources of nutrient availability. When nutrient deficiencies exist, chemical fertilizers, inorganic or organic, are applied by man to optimize biological and chemical relationships within the ecosystem.

Human habitation of the Moon will require environmental conditions similar to those on Earth where man evolved. Before bioregenerative closure within a lunar base, a synthetic atmosphere appropriate for human respiration must be prepared. Water, in quantities adequate for system function, must be synthesized. Higher plants must be included within the system for recycling purposes. Hardware, such as fiberglass containment vessels, can be manufactured from lunar regolith.

After preliminary development, implementation of a bioregenerative system composed of interdependent components of food production, waste management and utilization, and product synthesis will aid in the generation of a lunar ecosystem capable of supporting human life. Food will be produced from higher plants. Solid, liquid, and gaseous wastes must be managed to prevent disease or toxic compound release into the environment. These wastes will also be recycled since they contain vital components within a bioregenerative system. From waste recycling, essential products can be generated. Total system closure will only occur within a well-established lunar base after preliminary construction and development phases. Assuming an established lunar base, we will herein discuss some crucial aspects of a bioregenerative system. The oxygen cycle will not be discussed since regenerative oxygen extraction methods from ilmenite or magma electrolysis have been developed, and oxygen should not be limiting.

FOOD PRODUCTION— "FARMING" LUNAR SOIL

During the primary stages of lunar base construction and development, which might include 8 to 10 occupants, hydroponic systems may be used to grow plants for both food and partial gas exchange. Research is currently being conducted at the Kennedy Space Center (KSC) to develop and study hydroponic plant production systems for space habitats. Automated hydroponic systems would most efficiently utilize both area and mission specialists' time. However, as the size and number of occupants increases by an order(s) of magnitude during developmental phases (*Duke et al.*, 1985; *Burden and Angelo*, 1985) and total bioregenerative enclosure is required, lunar soil may be utilized for growing plants and as a deposition site for anaerobically digested residues. Although somewhat different from terrestrial rock and soil in composition and mode of formation, lunar soil possesses the precursor primary minerals of terrestrial soils. Major lunar minerals are olivine, pyroxene, and plagioclase feldspars (*Williams and Jadwick*, 1980). Since chemical weathering has not occurred on the Moon, mineral transformations to secondary products with greater stability have not occurred. Physical weathering induced by meteorite impacts has altered the mineralogy by forming glass and agglutinate (minerals in glass matrix) fractions. Olivines, pyroxenes, and volcanic glasses are some of the most soluble minerals in a chemical weathering environment on the Earth. Although relatively insoluble in water, their solubility is enhanced in the acidic environment produced during cropping.

Sources of acidity associated with the soil-plant system to promote mineral dissolution include (1) humification of residues, (2) plant root exudation, (3) acid-forming fertilizers, (4) hydration of Al, Fe, and to a lesser extent Mn ions, and (5) carbonate equilibria. Approximately 10% by weight of Apollo sample 12070

[1]The Land, EPCOT Center, Walt Disney World Co., P.O. Box 10,000, Lake Buena Vista, FL 32830-1000
[2]University of Florida, Soil Science Department, 2169 McCarty Hall, Gainesville, FL 32611
[3]University of Florida, Soil Science Department, 106 Newell Hall, Gainesville, FL 32611

was dissolved in weak acid (0.6-g sample in 350 ml 0.01 *M* salicylic acid) while 0.25% was dissolved in water during an 81-day incubation study (*Keller and Huang*, 1971). Ions essential for plants that dissolved from lunar soil include Mg, Fe, Ca, and low concentrations (approximately 10 μmol l^{-1} in acidic media) of K. In another study to determine the influence of lunar soil on higher plants, chlorophyll concentration was increased by 21-35% in tobacco callus as a result of enhanced Mg and Fe availability when compared to control treatments (*Weete and Walkinshaw*, 1972).

Essential nutrients that might be deficient in lunar soil include N, P, K, and some micronutrients. The small quantities of micronutrients required by plants may make it cost effective to import them from Earth, but macronutrients are required in large quantities. Lunar base fertilizers might, therefore, have to be produced for either soil or hydroponic plant-growing systems (see section on product synthesis).

A possible deterrent to usage of lunar soil for cropping might be the release of heavy metals, especially Ni and Cr, into the bioregenerative system. Constant cropping could also lower lunar soil pH to where Al^{3+} could reduce plant yield. In the soil pH range of 6.0-7.0, the dominant Al solution species would be the nontoxic $Al(OH)_3^0$ rather than Al^{3+} (*Lindsay*, 1979). Liming the soil with lunar fine soil fractions may be one solution. Lunar soil pH in water has never been determined by accepted soil testing methods, but the best available lunar soil simulants have a pH near 8.0. Therefore, the buffering capacity of the lunar fine soil fractions might maintain an adequate pH for cropping and secondary mineral neogenesis.

As on Earth, higher plants would assimilate CO_2. All plants that would be of interest occur in two groupings based on mechanism of CO_2 assimilation. At normal atmospheric CO_2 levels (340 mg l^{-1}), C-4 plants like corn fix CO_2 most efficiently, while at elevated CO_2 levels (1200 mg l^{-1}), C-3 plants like beans would have the advantage in CO_2 fixation due to reduced CO_2 loss via photorespiration (*Black*, 1986).

Initially, N_2 will have to be imported from Earth for generation of an atmosphere. It might be cost effective to generate the majority of plant-available N_2 by symbiotic N_2 fixation. Leguminous species fix atmospheric N_2 when infected with *Rhizobium*. These symbiotic bacteria use plant photosynthate for energy. Symbiotic N_2 fixation was increased fivefold when CO_2 was enriched to 1200 mg CO_2 l^{-1} as compared to fixation at ambient CO_2 levels (*Hardy and Havelka*, 1975). Growing legumes would promote greater usage of the CO_2 available from waste recycling (see section on waste management and utilization), as well as increase the N_2 availability in the soil for subsequent nonlegume crops. Since the volume of N_2 in the lunar base atmosphere is minute when compared to the terrestrial atmosphere, N_2 will have to be added as microorganisms reduce its concentration. Adsorbed on lunar soil surfaces are sources of N_2 and H_2. As H_2 is collected for ilmenite reduction, N_2 might be collected to supplement the lunar base atmosphere.

Implementation

A hypothetical 100 inhabitants would use at least 2100 liters of water daily (*Spurlock and Modell*, 1979), and require a minimum of 600 m^2 of hydroponic food production area (*Salisbury and Bugbee*, 1985). Estimates of food production from lunar soil will not be available until a high-fidelity lunar simulant is available for research. Waste water (water used for all purposes but toilets) could be stored in a fiberglass vessel manufactured from lunar regolith (*Ho and Sobon*, 1979) and supplied to plants growing in lunar soil through a drip irrigation system.

To prevent water loss, lunar soil will have to be confined within a fiberglass containment structure. Lunar minerals are anhydrous and would initially require substantial water. Without containment, water should disperse throughout the soil. Since 85% of crop plant roots are in the top 0.15 m of soil, container depths of 0.6 m should be sufficient for total root proliferation. On the soil surface, CO_2 could be applied through vented piping to maintain at least 1200 and 340 mg CO_2 l^{-1} within the C-3 and C-4 crop canopies, respectively. Approximately 100 kg of CO_2 will be respired per 100 occupants per day in the lunar base (*MacElroy et al.*, 1985). Maximally, C-3 plants can fix 60 μmol CO_2 sec^{-1} m^{-2} when neither light nor CO_2 is limiting (*Challa and Schapendonk*, 1986). This translates to 136 kg of CO_2 fixed per day per 600 m^2. Calculations indicate that 600 m^2 of mature crops, photosynthesizing at theoretical maximum limits, could recycle the CO_2 produced by 100 occupants. Assuming a one-to-one relationship between CO_2 fixation and plant dry weight, and a per person food requirement of 0.6 kg day^{-1} (*MacElroy et al.*, 1985), then daily respiration from 100 occupants plus the average daily CO_2 generated from waste recycling, would supply the minimum food requirements if the crop harvest index is at least 34%. Plant species, planting density, and crop stress levels will of course influence these calculations.

Anaerobically digested plant biomass and sewage sludge residues (see section on waste management and utilization) will be applied to the soil to aid in moisture retention, increase particle aggregation and soil structuring, and subsequently soil gaseous exchange. Select groups of introduced heterotrophic microorganisms could aid in the mineralization of N, P, and micronutrients from organic substrates. Introduced chemoautotrophic microbes could aid in the conversion of ions to a more plant-preferred ionic species. Algae could be applied to the soil surface to reduce gaseous N losses (*Alexander*, 1977).

Soil-water relationships will be of extreme importance. The approximate bulk density of lunar soil is 1.5 g cm^{-3} (*Carrier et al.*, 1973). With a cropping area of 600 m^2 and a depth of 0.6 m, the soil would weigh 540,000 kg by terrestrial standards. Terrestrial basalt, ground to approximate particle size of lunar samples, has a water holding capacity of 4.3% at 0.33 bar as determined by the pressure membrane extraction technique (G. W. Easterwood, unpublished data, 1988). Assuming the same water-holding capacity, lunar soil by weight could contain at least 23,220 liters of water, equivalent to the waste water of 100 occupants for 10 days. Soil moisture content could be monitored with a neutron probe at various depths to ensure optimal moisture and aeration for plant roots.

Most of the water applied to the cropping area will be transpired into the atmosphere, reclaimed by condensation, distilled for purification, and stored directly in the potable water storage tank. Plants transpire approximately 225 kg of H_2O per kilogram dry weight biomass produced (*Salisbury and Ross*, 1978). Wheat, for example, with a life cycle of 60 days and biomass production of 3120 kg on 600 m^2 of cropping area (*Salisbury and Bugbee*, 1985), would transpire an average of 11,700 liters of H_2O per day.

Crops transpire more than three times the occupant water requirements, leaving surplus potable water that could be used for fish production. With intensive aquacultural practices, it is possible to produce 200 kg of fish m^{-3} of water per year (*Balarin and Haller*, 1983). A tank containing 8400 liters of water (11,700

total from plant transpiration—3000 for occupants, 300 for solid waste transportation) could produce 16,800 kg of fish annually. Fish, like tilapia (*Tilapia aurea*), can feed on processed plant biomass. Possibly some of the crop biomass or residual solid from the anaerobic digestion process could be processed for fish food (*Degani et al.,* 1983). To reduce the buildup of toxic compounds from fish excrement, waste water can be recycled through the soil system providing supplemental N_2 fertilization to growing plants. Solid wastes may be removed from the water and combined with the human biological wastes.

WASTE MANAGEMENT AND UTILIZATION

Wastes, defined as biomass from crops and the solid, liquid, and gaseous biological wastes from the occupants, will be important sources of recycled CO_2, H_2, O_2, N_2, P, K, and energy within the lunar base ecosystem. Of the wastes that will be produced, gases such as CO_2 will be removed during atmospheric recycling through the crop growing area. Waste water will be recycled by transpiration through the soil-plant system. Daily production of occupant solid waste will average 109 g dry weight of feces per person (*MacElroy et al.,* 1985), and 2340 kg of dry weight inedible plant biomass per 60 days on 600 m^2 of growing area, assuming wheat production of 1.3 kg seed m^2 with a harvest index of 0.25 (*Salisbury and Bugbee,* 1985).

Solids will be recycled by biological conversion processes. Biological conversion of solid wastes will be more suitable for energy extraction and nutrient recycling than will thermal conversion (*Chynoweth,* 1987). Anaerobic digestion of the biomass will produce CH_4 and CO_2 gases, and a residual concentration of N, P, and K in the digestion effluent. Utilizing the latest technology in anaerobic digestion design, 92% conversion of biodegradable substrates (1:1 ratio of sludge:plant biomass) into gaseous products may be obtained with a loading rate of 91 g of dry weight biomass per 28.32 liters of digester volume per day. Total gas yield is 780 liters per kilogram of dry weight volatile solids (*Gas Research Institute et al.,* 1986).

Implementation

Sewage plumbing will be independent from waste water plumbing. Following a toilet discharge, sewage will pass through a macerator to reduce particle size prior to storage. Small biomass particle size lowers retention time within the anaerobic digester and facilitates greater degradation. Inedible crop biomass can also be milled and stored separately for future anaerobic decomposition.

Optimal ratios of sewage to plant biomass will be pumped from the storage tanks and combined within an anaerobic digester(s) for degradation of materials and generation of gases and nutrients. Products of the anaerobic digestion are gases (64% CH_4 and 36% CO_2 per unit volume) and liquid effluent containing N, P, and K. Approximate nutrient concentrations in the effluent after digestion of water hyacinths, for example, were 289 mg NH^{4+} l^{-1}, 12 mg P l^{-1}, and 123 mg K l^{-1} (*Reddy,* 1988). Gases will be separated and stored. Residual solids can be applied to amend the soil or used as fish feed (*Degani et al.,* 1983). Solid-free digestion effluent that emerges from the digester essentially sterile (*National Academy of Sciences,* 1977) may be mixed with waste water to produce a suitable fertilizer for crops through the drip irrigation system.

PRODUCT SYNTHESIS

The major products that must be produced on the Moon are oxygen and water. Water could be generated from the reduction of ilmenite with H_2, and O_2 produced from sequential electrolysis (*Gibson and Knudsen,* 1985; *Williams,* 1985). Since a hydrogen sink exists in water production, resupply of H_2 will be imperative. Methane from anaerobic digestion may be processed to produce H_2 and CO_2. Direct reduction of ilmenite with methane has also been studied by Russian scientists (*Reznichenko et al.,* 1983).

During crop production on the Moon, a phosphate sink may develop that would require input into the system. Orthophosphate ions are very reactive and relatively immobile in soils. Once applied, orthophosphate may be adsorbed to mineral surfaces and/or precipitated from solution as an insoluble Ca, Fe, or Al phosphate (*Tisdale and Nelson,* 1975). In extremely unfavorable environments, up to 90% of applied fertilizer $H_2PO_4^-$ is unavailable to plants from "fixation" mechanisms (*Stevenson,* 1982). Trace quantities of apatite and whitlockite minerals exist within the lunar regolith (*Williams and Jadwick,* 1980) and may provide the balance of deficient quantities of orthophosphate. Mining these minerals for P may be as essential to lunar agriculture as mining ilmenite will be for water and oxygen production. To produce water-soluble fertilizers, however, strong acids will have to be produced. Complex fertilizer technology for processing lunar regolith could only exist within a well-established and self-sustaining lunar base.

Implementation

Methane, produced from the anaerobic digestion process, will have to be separated from CO_2 for generation of H_2 or direct reduction of ilmenite with CH_4. Conventional separation of CO_2 and H_2S from CH_4 may be accomplished by the Girbotol or Monoethanolamine process (*Shreve,* 1967). Concentrations of less than 0.01% CO_2 by volume in the H_2 gas may be obtained by this regenerative method. Hydrogen gas may be synthesized by the Steam-Hydrocarbon Reforming process (*Shreve,* 1967), which chemically processes CH_4 into CO_2 and H_2. Again, the Girbotol process could be employed to remove CO_2. Since temperatures fluctuate between 102K and 384K during the 14-Earth-day lunar day and 14-Earth-day lunar night, cryogenic methods of gas separation may provide a low-energy alternative compared to chemical methods.

From sewage and crop biomass, approximately 18,018 kg (14,040 kg from 6 cropping periods on 600 m^2 and 3978 kg from feces of 100 occupants) of dry weight wastes should be generated per year. With a 92% solid waste bioconversion efficiency, and 780 liters of gas generated per kilogram of solid, with 64% of the gas CH_4, approximately 8,275,018 liters of CH_4 would be produced annually. Assuming 100% efficiency during the steam-hydrocarbon reforming process, and reduction of ilmenite without any losses or inputs into either process, approximately 13,400 liters of water could be produced. Direct reduction of ilmenite with CH_4 might reduce the number of intermediate steps and energy requirements.

INTEGRATING A SYSTEM: FARMING, WASTE MANAGEMENT, AND PRODUCT SYNTHESIS

This paper attempts to integrate the interdependent components of food production, waste management and utilization, and

product synthesis into a theoretical working regenerative system that could support a lunar base. Each component with respect to the terrestrial environment has been studied extensively, but their integration for maintenance of life support systems has never been attempted.

Crops with different mechanisms of CO_2 fixation should be grown in separate greenhouse modules so that maximal yield can be obtained in association with life support requirements. For example, lunar base atmosphere may be cycled through an agricultural module with C-4 plants such as corn, whose CO_2-fixing enzyme possesses a high affinity for CO_2. Another module containing plants with the C-3 pathway of CO_2 fixation could best utilize the elevated crop canopy CO_2 concentrations from CO_2 generated by the anaerobic digestion process. Crop rotation within agricultural modules will be important as leguminous crops fix N_2 in the soil for subsequent use by nonleguminous crops. The modular concept would not only permit easy expansion of crop production area with lunar base growth and development, but would also provide isolation of possible plant pathogens if crops encounter disease.

Agricultural modules will probably have to be covered with lunar regolith for radiation shielding. Plants grow well under artificial lighting, but supplying lamps from Earth would be prohibitive. Advances are occurring in light pipe and fiber optic technologies that may permit piping in selected wavelengths of sunlight. Also, a whole series of crop cultivars, adapted to the lunar day/night cycle, may have to be developed.

Advanced sensor technology coupled to artificial intelligence systems will control environmental parameters such as light intensity, temperature, soil moisture, relative humidity, and CO_2 and O_2 concentrations. Computerized infrared camera systems will scout for and identify causes of plant stress. "Smart" robots will be used to plant, cultivate, and harvest crops to provide a mission specialist adequate time for experimentation. After harvest, edible crop portions can be sent to a centralized processing and storage center. Transpiration water, reclaimed by consendation and distilled, can be stored in the potable water storage tank. Waste water, generated from lunar base occupants and aquacultural systems, will be stored, mixed with digester effluent, and applied to the soil-plant system through drip irrigation. A portion of the crop biomass, after milling, can be used for fish feed and the remainder sent to a centralized waste control center for anaerobic digestion.

At the waste control center, proper ratios of sewage and biomass can be mechanically mixed and injected into anaerobic digesters. Processed digester effluent can be transported to the agricultural modules for mixing with waste water. Residual digester solids may be used as fish feed (*Degani et al.,* 1983) or applied to the soil-plant system. A flow chart of ecosystem wastes and water is given in Fig. 1. Gases from anaerobic digestion may be segregated and processed to produce H_2. Carbon dioxide, collected during processing, will be returned to the C-3 greenhouse module. Hydrogen product gas will be sent to mining operations for the reduction of ilmenite.

CONCLUSIONS

Conservation and recycling of all solids, liquids, and gases within a bioregenerative lunar base will be of extreme importance. A closed loop Controlled Ecological Life Support System must be designed around food production, waste management and utilization, and product synthesis.

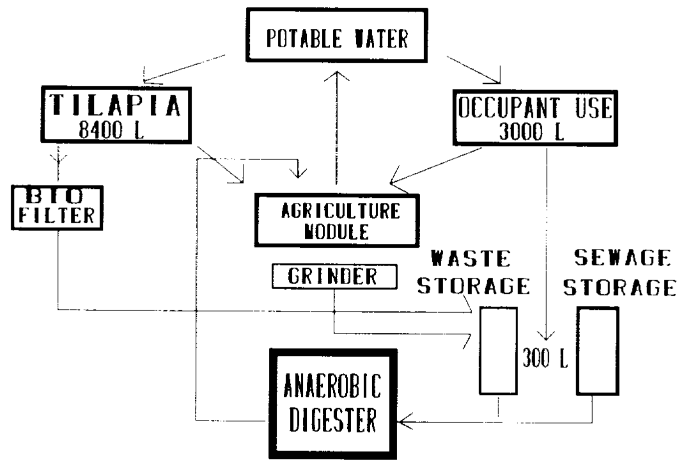


Fig. 1. Theoretical flow chart of wastes and water in lunar base CELSS.

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